Borehole-to-Surface Electrical Resistivity Monitoring of a Salt Water Injection Experiment

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Summary

A field experiment was conducted at the University of California Richmond Field Station to demonstrate the sensitivity of borehole to surface resistivity measurements in ground water investigations. A quantity of saline water was injected into a fresh water aquifer while the resistivity was monitored using a multi-channel borehole to surface system. Two experiments were conducted using different receiver electrode arrays and salt water slugs of different salinity. The data was interpreted using a three-dimensional resistivity modeling program, and compared to hydrologic measurements taken during the injection. In addition to demonstrating the sensitivity of subsurface arrays, the measurement of bulk resistivity identified a ground water flow pattern not detected by hydrological measurements.

INTRODUCTION

Of all the geophysical techniques, the electrical methods have had the most widespread use in ground water investigations because pore water resistivity is directly related to bulk earth resistivity. In field surveys, the emphasis has been on surface electrical techniques. However, the problem with this approach is that measurements are insensitive to contaminants if they are too deeply buried or if their concentration is low (Wilt et al., 1983). Further, such surveys are usually strongly influenced by the inhomogeneous near surface layer (Asch and Morrison, 1989).

If the resistivity measurements are made downhole or with combinations of downhole and surface current sources then the situation improves significantly. In a numerical study using three dimensional resistivity models Wilt and Tsang (1985) found that an order of magnitude increase in sensitivity can be achieved when the current source is placed downhole and within the contaminant zone.

EXPERIMENT DESIGN

Experiments using a borehole to surface configuration took place in February 1988 and February 1989 at the University of California Richmond Field Station, an industrial area adjacent to the San Francisco Bay and about six miles northwest of the Berkeley Campus.

Eight wells were drilled to depths ranging from 35 to 40 meters (Figure 1) through a section of unconsolidated clays and silt with intermittent lenses of sand and gravel.

All the wells are cased with PVC plastic. Two of the wells, INJ and EXT, are 6 inch in diameter and were designed for fluid injection and withdrawal experiments; these wells have steel sections for current injection. The remaining six holes (OBS1-OBS6) are 4 inch diameter wells drilled to depths ranging from 30 to 35 meters. These wells are open at the bottom and designed for use in water level measurement, downhole water sampling, and subsurface electrical potential measurements.

During the first experiment resistivity measurements were made by injecting current at the downhole metal segments north-south and east-west profile lines that intersect at well INJ. All electrodes were wired into a nearby building and resistivity measurements were made from this one location. For the second experiment, more azimuthal information was obtained by adding receiver electrode lines between the north-south and east-west lines (Figure 1).

Piezometric levels were measured in the wells at various dates. These measurements showed that under undisturbed condition, flow in the confined aquifer was from North to South and the average gradient of the piezometric level was about 0.003. Several pumping tests were carried out in different wells to calculate hydrologic properties of the aquifer. Values of drawdown from observation wells 1, 4, 5, and 6 due to pumping of Well INJ showed that there is a distinct difference between transmissivity data obtained from Wells 1 and 6. The analysis of this data indicates that the transmissivity of the gravel formation at this location is largest in the West-East direction. Note that these curves represent a point measurement and are aliased in azimuth about the injection well so that they do not sample the bulk groundwater flow in all directions.

A total of 25,000 gallons of salt water was injected into a gravel aquifer at 30 m depth. The conductivity of the native ground water and the injected salt water were monitored throughout the experiment with a conductance meter. Conductivity probes were located in the injection well just above the screen and at the bottoms of the observation wells. The conductivity of the native ground water was measured to be 50 to 60 mS/m (20 $\Omega \cdot m$ to 17 $\Omega \cdot m$) and the injected salt water was 1.3 S/m and 0.88 S/m (0.76 $\Omega \cdot m$ and 1.13 $\Omega \cdot m$) for the first and second experiment, respectively.

Assuming an aquifer thickness of 3 m and a porosity of 20 %, it is easy to show that a 25,000 gallon (94.5 cubic meter) injection would result in a cylindrical anomaly of 7 m radius under conditions of isotropic plug flow. No changes in ground water conductivity were measured at the observation wells 15 m away.

RESISTIVITY MONITORING

Base line resistivity data was collected before salt water injection began and measurements were taken every day during the injection and extraction procedure. The data was acquired by energizing the 30 m or 40 m transmitter electrodes in well INJ in concert with the remote transmitter electrode and measuring 17 dipole potentials along any half of one line at a time.

The pole-dipole measurements were superimposed to create dipole-dipole potentials. Figure 2 is a plot of the difference between the maximum injection data and the pre-injection data. This represents a maximum anomaly of about 40 percent.

A three-dimensional finite difference algorithm developed by Dey and Morrison (1980) was used to simulate the salt water injection experiment. Computer memory limitations constrained the finite difference mesh size to 55 by 16 by 20 nodes on the IBM 3090. This made it difficult to include the layered stratigraphy and to adequately discretise the area around the current source while allowing the potential to fall off properly at the edges of the mesh.

The layer model used to represent the geology of the field site has a 2 m thick surface layer of 17 $\Omega\cdot$m underlain by a 38 m thick 11 $\Omega\cdot$m layer, all over a 50 $\Omega\cdot$m halfspace. The salt water slug was simulated by a 1 ohm-m tabular block 3 m in the z direction, 13 m in the y direction, and from 8 m to 10 m in the x direction. Model 1 is centered on a transmitter electrode at 30 m depth, while models 2 through 4 are progressively off-center to the left. These models correspond roughly to the geology at the Richmond Field Station.

Figure 3 is a plot of calculated potential differences due to a dipole transmitter with electrodes at the 30 m and 40 m depths. The dipole-dipole voltages from the models can be used to interpret the curves in Figure 2. Salient characteristics of these model curves include an anomaly increase on the side corresponding to the direction of block displacement and a zero-crossing shift away from the direction of displacement. Also, the curves for the displaced blocks intersect the curve for the centered block. This intersection occurs at lower receiver numbers for greater block displacement.

Analyzing the data of Figure 2 in light of these model results indicates that the direction of maximum transmissivity is northwest. The amplitude of the northwest-southeast curve is maximum to the left, which is the northwest side of the line. The zero crossing is displaced to the southeast, indicating displacement to the northwest. For the other three lines, maximum displacements occur (in order of magnitude) to the west, north, and northeast. Since the northwest-southeast data shows the greatest amplitude, this must correspond to the direction of maximum bulk ground water flow.

The potential gradients, because of the limited mesh size, are not approximated correctly by the program and the potential does not fall off properly. This results in a noisy looking curve. With these modeling limitations the program can give only a crude qualitative approximation of the field situation for such a small and relatively deep body. A larger mesh would allow for better discretisation of the anomalous body. The tabular models could then be replaced with much more accurate 3-dimensional representations of the saline intrusion and the complex layering sequence at the site could be better represented.

Currently, run time for these models is about 20 minutes on the IBM 3090. This, coupled with the small mesh size, makes successive forward modeling or data inversion impractical and prohibitively expensive.

CONCLUSIONS

The field experiment described here was successful in demonstrating that electrolytic contaminants may be detected with borehole-to-surface electrical measurements. The injected plume of salt water moved asymmetrically into the north-west quadrant from the injection hole. The pressure during drawdown tests indicated major transmissivity to the east although no test wells are available to measure transmissivity to the northwest. The results suggest strong channel flow paths that would not be determined by a limited number of observation wells, but which are clear in the resistivity results.

The multi-channel resistivity monitoring system is capable of gathering data accurately enough to map subsurface groundwater flow. The chief limitation to this system lies in the lack of adequate interpretive tools. The development of a new program with greatly a expanded mesh size and quicker run time would enable more detailed and accurate interpretation of field data. If the plume boundary could be accuratly modeled, the porosity and transmissivity of the aquifer could be determined. This method would then move from the realm of reconnaissance and detection to precise engineering application.

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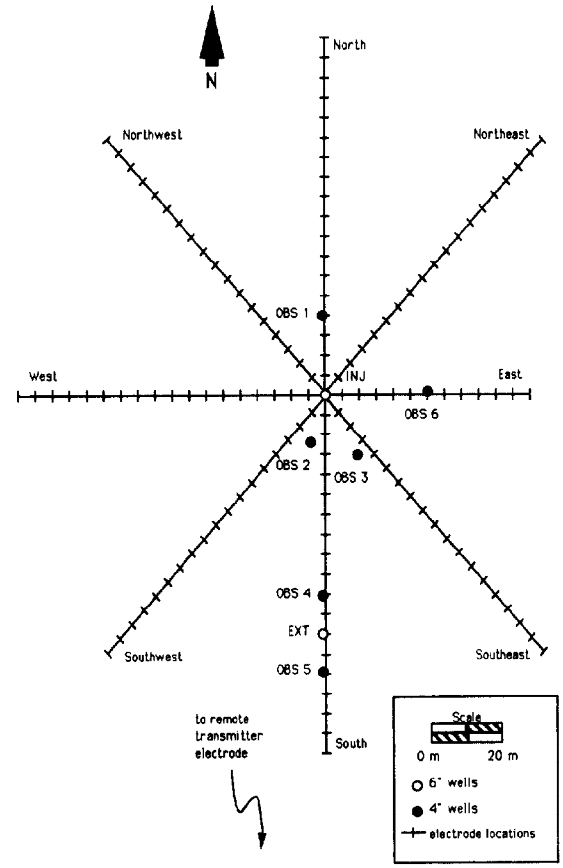

FIG. 1. Plan map of well field and resistivity array at Richmond field station.

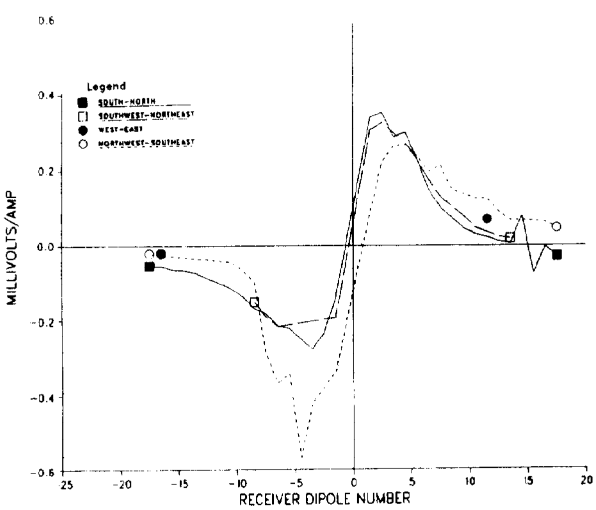

FIG. 2. Plot of potential difference data for bore-hole-to-surface configuration. Preinjection data subtracted from maximum injection data to generate these curves.

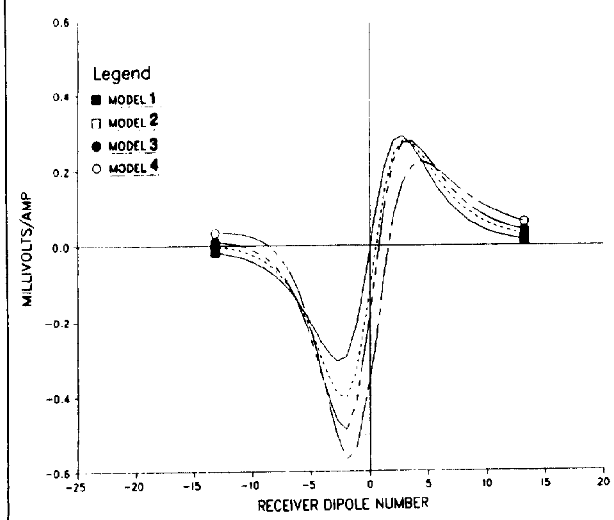

FIG. 3. Curves of potential difference calculated by finite-difference algorithm.